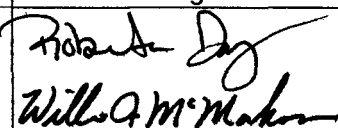
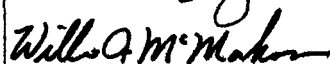
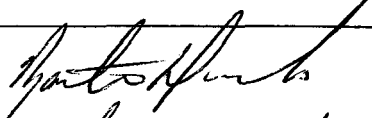
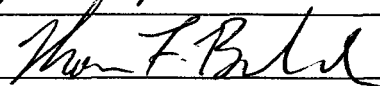


Engineering Design File

Leachate Contaminant Reduction Time Study



Form 412.14
07/24/2001
Rev. 03

1. Title: Leachate Contaminant Reduction Time Study				
2. Project File No.: NA				
3. Site Area and Building No.: NA			4. SSC Identification/Equipment Tag No.: NA	
5. Summary: <p>Concentrations of selected design inventory constituents in INEEL CERCLA Disposal Facility (ICDF) landfill leachate were evaluated to estimate leachate chemical characteristics during the 15-year operations period and the 30-year post-closure period. The purpose of the study was to estimate leachate constituent concentrations to support various design evaluations including:</p> <ul style="list-style-type: none"> • Identifying a conservative estimate of the leachate chemical characteristics as a basis for assessment of landfill liner/leachate compatibility; • Identifying a conservative estimate of the leachate chemical composition to assess worker exposure to landfill contaminants in the leachate evaporation ponds. <p>Three approaches were taken to evaluate the leachate as described below:</p> <ol style="list-style-type: none"> 1. To identify potential maximum leachate concentrations in the landfill, a geochemical model was used to simulate the chemical nature of the leachate at the approximate moisture content of the compacted waste soil. 2. To identify the potential loss of constituents from the waste soil in leachate during the 15-year operating period, a spreadsheet-based analytical solution was used. 3. To identify potential concentration of leachate constituents outside of the landfill during the 30-year post-closure period, a numerical simulation model (i.e., STOMP, the same model used for fate and transport simulations to evaluate groundwater remedial action objectives) was used to estimate the volume and characteristics of the leachate. <p>The geochemical modeling indicates that pore water within the compacted waste soil is expected to be a brackish to saline water (approximately 0.5 molar ionic strength) dominated by sodium and sulfate and buffered by carbonates to a pH of around 8.0. The analytical solution indicates that as much as 20% of the inventory masses of the most mobile constituents (e.g., iodine and technetium) may be removed from the landfill during the 15-year operation period. The numerical simulations of constituent transport during the 30-year post-closure period indicated that less than 1% of the contaminant mass would be expected to leave the landfill as leachate during the post-closure period. Because of the high degree of uncertainty regarding the actual rate of waste soil placement in the landfill and the actual placement of specific waste soil, conservative assumptions were made that are believed to maximize apparent leachate concentrations for these evaluations.</p>				
6. Review (R) and Approval (A) and Acceptance (Ac) Signatures: (See instructions for definitions of terms and significance of signatures.)				
	R/A	Typed Name/Organization	Signature	Date
Performer		Roberta Day/ CH2M HILL William J McMahon/ CH2M HILL	 	05/14/02
Checker	R	(Same as Independent Peer Reviewer)		05/14/02
Independent Peer Reviewer	A	Marty Doornbos/ BBWI		05/14/02
Approver	A	Thomas Borschel/ BBWI		05/14/02

ENGINEERING DESIGN FILE

Requestor	Ac	Don Vernon/ BBWI	<i>D. Vernon</i>	05/14/02
7. Distribution: (Name and Mail Stop)		M. Doornbos, MS 3930; D. Vernon, MS 3930; T. Borschel, MS 3930		
8. Records Management Uniform File Code (UFC):				
Disposition Authority:			Retention Period:	
EDF pertains to NRC licensed facility or INEEL SNF program?: <input type="checkbox"/> Yes <input type="checkbox"/> No				
9. Registered Professional Engineer's Stamp (if required)				

ABSTRACT

Concentrations of the design inventory constituents in the INEEL CERCLA Disposal Facility landfill leachate were simulated over the 15-year operations period and 30-year post-closure period. The purpose of the study was to examine the chemical nature of the leachate and the change in leachate concentration over time. The results provide a basis for assessment of leachate/liner compatibility, and also support evaluation of worker exposure to waste constituents that may be present in the facility leachate evaporation ponds. Three approaches were taken to evaluate the leachate.

1. A geochemical model was used to predict the general chemical characteristics of the leachate. A group of design inventory constituents screened on the basis of concentration and representing 99% of the total mass were equilibrated with pore water within the compacted waste soil in the landfill. The leachate is predicted to be a brackish to saline water dominated by sodium and sulfate with ionic strength of approximately 0.5 molar and buffered by carbonates to a pH of around 8.0. The modeled pore water concentrations provide the most conservative basis for liner compatibility evaluation.
2. A spreadsheet calculation was used to estimate potential landfill design inventory constituents removed from the landfill during the 15-year operating period. The spreadsheet calculation simulated partitioning to the solid phase via adsorption, radioactive decay, and leachate removal from the landfill. The results indicate as much as 20% of the inventory masses of the most mobile constituents (e.g., tritium and iodine), about 5% of the technetium-99, and less than 1% of the uranium isotopes and neptunium-237 are expected to be removed from the landfill during the operation period.
3. The STOMP model was used to simulate potential landfill design inventory constituents removed from the landfill during the anticipated 30-year post-closure period with the final cover in place. The results of the 30-year post-closure transport simulation indicate less than 1% of the inventory masses of even the most mobile constituents are expected to be removed from the landfill during the post-closure period (i.e., following placement of the final cover).

CONTENTS

ABSTRACT	iii
ACRONYMS.....	vii
1. INTRODUCTION.....	1-1
2. GEOCHEMICAL MODELING	2-1
2.1 Screening Process	2-1
2.2 General Principles.....	2-3
2.3 Site-Specific Methodology	2-3
2.4 Results of Geochemical Modeling.....	2-5
3. LEACHATE GENERATION RATE AND CONTAMINANT REDUCTION OVER TIME.....	3-1
3.1 Leachate Generation	3-1
3.1.1 Introduction	3-1
3.1.2 Approach	3-1
3.1.3 Methodology	3-1
3.1.4 Simulation Output and Discussion	3-3
4. LEACHATE GENERATION AND CONTAMINANT REDUCTION DURING POST-CLOSURE PERIOD	4-1
4.1 Leachate Generation Simulation.....	4-1
4.1.1 Introduction	4-1
4.1.2 Approach	4-1
4.1.3 Methodology	4-1
4.1.4 Simulation Output and Discussion	4-4
5. CONCLUSIONS.....	5-1
6. REFERENCES.....	6-1
Appendix A—Constituent Solubility Modeled Using PHREEQC	
Appendix B—PHREEQC Input and Output Files	
Appendix C—Leachate Generation Calculations 15-Year Operations Period	
Appendix D—Leachate Concentration Estimates for the 30-Year Post-Closure Period	
Appendix E—PHREEQC Constituent Screening	

Tables

2-1.	Calculation of mineral abundance in site soils.....	2-4
2-2.	Results of PHREEQC simulation: calculated constituent concentrations in leachate (no partitioning applied).....	2-5
4-1.	Summary of soil properties and moisture content-aqueous pressure relationship curve fit parameters.	4-4
4-2.	Summary of soil hydraulic and contaminant transport properties.	4-4
4-3.	Contaminant distribution coefficients and weighted averages for the different surrogates and model layer types.	4-4
4-4.	Summary of Post-Closure Leachate Modeling Results at 0.0001 m/yr Recharge Rate.....	4-6

Leachate/Contaminant Reduction Time Study

1. INTRODUCTION

The purpose of the Leachate/Contaminant Reduction Time Study is to document the estimated composition of both the leachate and the landfill waste soil mass over the periods of operation (15 years) and post closure (30 years) at the Idaho National Engineering and Environmental Laboratory's (INEEL) proposed INEEL CERCLA Disposal Facility (ICDF) landfill. During operation and post-closure periods, the leachate will flow through the leachate collection system and will be discharged to the evaporation pond. Results of this study will be used to evaluate compatibility of the synthetic and natural liner components with the leachate and to estimate pond water composition over time to support other assessments.

The evaluations are conducted separately based on the operations period (using two different approaches) and the post-closure period (using one method). For the operation period, the leachate concentrations were simulated using both a geochemical model (Section 2) and a spreadsheet-based analytical solution method (Section 3). For the subsequent 30-year post-closure period, a numerical simulation was performed using the Subsurface Transport Over Multiple Phases (STOMP) code, assuming placement of the final cover (Section 4).

The geochemical model was used solely to predict general chemical characteristics of the leachate for later use in the leaching transport models. Because of the voluminous list of constituents, the geochemical modeling screened the design inventory elements down to those that account for greater than 99% of the total mass identified in the design inventory. Section 2 provides a detailed description, assumptions, and results of this evaluation.

The spreadsheet-based analytical solution was used to estimate the potential landfill design inventory constituents removed from the landfill during the 15-year operation period. This evaluation partitioned the design inventory mass of all of the contaminants of concern between soil and leachate aqueous concentrations on the basis of partitioning coefficients (which are used to estimate the degree of adsorption to soil mineral surfaces). The spreadsheet-based analytical solution did not account for or include any solubility limitations. Leaching rates were applied, along with radioactive decay rates (where applicable) to determine the possible mass removal from the landfill over time. Plots were constructed of potential landfill mass concentrations and landfill leachate concentrations over time during the 15-year operating period. Section 3 provides a detailed description, assumptions, and results of this evaluation.

The STOMP simulation, a numerical simulation of the 30-year post-closure period with the final cover in place, also included the entire design inventory mass of all of the contaminants of concern. The model grid and construction was a subset of the model described in EDF-ER-275 that included the waste and operations layers. The top of the clay layer, where the liner system functions to prevent downward flow, was set to act as a no-flow boundary. Two numerical seepage face boundaries on top of the clay layer and on both sides of the ICDF model domain provided the means to evaluate the flow and contaminants exiting the model. Section 4 provides a detailed description, assumptions, and results of this evaluation.

Details regarding constituent screening, calculations, simulations, and modeling results used in this study are provided in the following appendices:

- Appendix A—Constituent Solubility Modeled Using PHREEQC

- Appendix B—PHREEQC Input and Output Files
- Appendix C—Leachate Generation Calculations 15-Year Operations Period
- Appendix D—Leachate Concentration Estimates for the 30-Year Post-Closure Period
- Appendix E—PHREEQC Constituent Screening.

2. GEOCHEMICAL MODELING

The geochemical model was used to predict the general chemical characteristics of the leachate. A group of the design inventory was screened to identify major constituents for geochemical modeling. Because the geochemical modeling activity is computationally intensive, individual constituents accounting for less than 0.01% of the design inventory were excluded from the geochemical modeling activity. The retained constituents account for more than 99.9% of the contaminant mass identified in the design inventory. Additional details regarding the screening are provided in Section 2.1 and Appendix E.

2.1 Screening Process

Initial activities included the screening of constituents. Quantities of inorganic (non-radioactive) and organic compounds were reported as total kilograms (kg), whereas concentrations of radionuclides were provided as total curies in the "INEEL CERCLA Disposal Facility Design Inventory" (EDF-ER-264). These were converted to kg using published half-lives and atomic mass for each isotope. For elements with reported concentrations of radioactive and non-radioactive forms, the isotope masses were summed, although in these cases the radioactive concentrations were far less than those of non-radioactive isotopes. The source of radioactive constituents was Table D-3 from the design inventory (EDF-ER-264).

The screening process is illustrated in Figure 2-1. Two screening exercises were completed. The first was based solely on partition coefficient (K_d) values. As shown on the portion of Figure 2-1 marked "1", all elements with K_d values less than 20 were considered significantly leachable during the operations period and were therefore included in the leachate generation calculations presented in Section 4. A K_d of 20 corresponds to 1% of the waste mass leaching into solution. These constituents were assumed to have no solubility controls, and were assumed to partition to the aqueous phase according to their K_d values. The resulting list of elements, including their milligrams per kilogram (mg/kg) concentrations, K_d values, and corresponding aqueous concentrations, is provided in Appendix E as Table E - 1. The constituents with K_d values greater than 20 are displayed in Table E-2.

The second screening exercise (marked "2" on Figure 2-1) was based on the nature and concentration of inventory constituents. All constituents existing in solution as anions were included, regardless of their concentrations in the inventory. Plutonium is predominantly in anionic form above pH 8, and uranium carbonate species are anionic, so both of these elements were included, even though they are assumed to be cations in many studies. Organic compounds were assumed to be neutral species. All inventory organics were eliminated because none was over 1% of the total mass fraction, calculated by dividing the total kg for a given compound by the assumed total waste stream mass of 5.85×10^8 kg. Inorganic constituents were screened to include only those that constituted over 0.01% of the total mass fraction. Since there is a minimal amount of organic constituents in the design inventory, 1% was selected as the criteria to identify the major chemical species contributing to the leachate chemistry. Similar screening was used for the inorganic species with the intent to identify the species that contribute 99.99% of the constituents in the leachate. The final list of constituents for this screening exercise is shown in Appendix E as Table E-3. Those constituents that were screened out are provided in Table E-4.

The second list was included in a geochemical model to correct for solubility in the leachate before being passed to the leachate generation calculations.

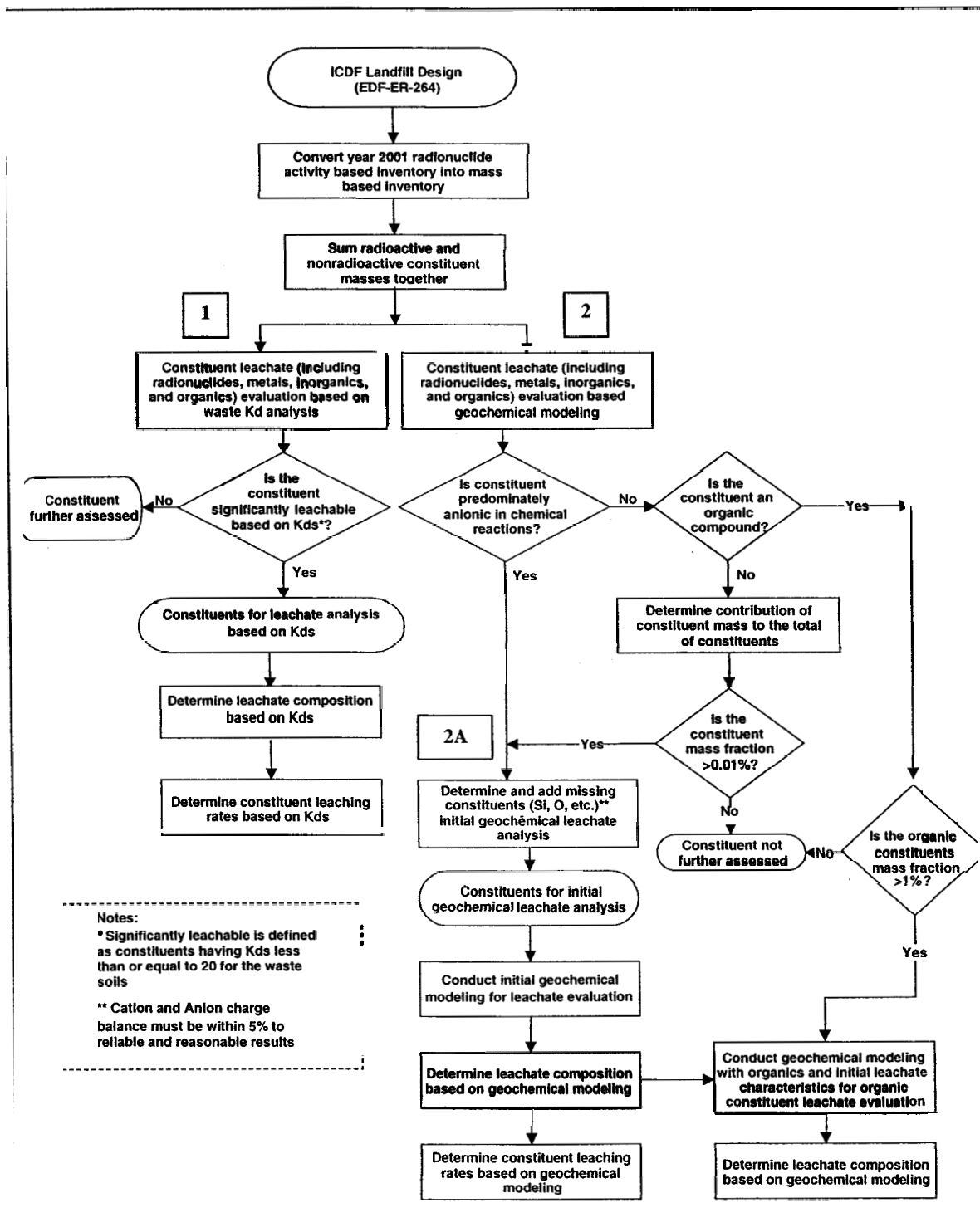


Figure 2-1. Screening process flowchart for geochemical evaluations.

2.2 General Principles

The geochemical model PHREEQC, v. 2.5 (Parkhurst and Appelo 1999), was used for this study, using a recently released database, LLNL.DAT, which contains species and mineral phase data for all of the screened elements. PHREEQC receives as input all aqueous concentrations of constituents in the infiltrating water, along with quantities of all mineral phases believed to be present in the landfill material. Geochemical conditions are also specified, namely the pH, redox potential, and the presence of atmospheric gases (O_2 , CO_2 , etc.). These conditions may either be set or allowed to change as the system equilibrates.

The model takes into account all elements reported and, using the database, calculates concentrations and activities (concentrations corrected for ionic strength) of all aqueous species present. For example, calcium exists in various aqueous forms including Ca^{2+} , $CaHCO_3^+$, $CaCl^+$, etc. Saturation with respect to applicable mineral phases is also calculated by comparing the ion activity product with the solubility product constant (K_{sp}) for a given mineral. For example, the mineral calcite ($CaCO_3$) has a K_{sp} of approximately $10^{-8.4}$. This means that under equilibrium conditions, the product of the aqueous activities of the ions Ca^{2+} and CO_3^{2-} is $10^{-8.4}$. If this product is greater than the K_{sp} , the solution is said to be supersaturated with respect to calcite, and undersaturated if the opposite is true. This demonstrates the importance of calculating the free concentration of mineral constituent ions such as Ca^{2+} . Other ions in solution may complex Ca^{2+} or reduce its activity by contributing to higher ionic strength. PHREEQC calculates these effects for all input elements and minerals.

One of the many other features of the PHREEQC model is the ability of the user to assign equilibrium conditions to selected mineral phases. In this way, if minerals are known or suspected to exist at a site, the user may instruct PHREEQC to dissolve the necessary amounts of those minerals to achieve equilibrium with the surrounding solution. This feature was used in the present study.

2.3 Site-Specific Methodology

The first step in the geochemical model setup was to input the infiltrating water chemistry. The average annual rainfall at the site was assumed to be approximately 8 in./yr (NOAA 1989). In addition, site water supplies will be used for dust suppression and compaction during the operating period at an estimated rate of 10,000 gallons per week (EDF-ER-269). This corresponds to an equivalent of 1.43 in./yr in applied water. The infiltrating water will therefore have a proportion of 85% rainwater and 15% applied water. Major chemical constituents for each water source were input to PHREEQC, using an average rainwater analysis (Brownlow 1996) and site records for Well CPP-1.^a The two waters were mixed in the proportions described above and the resulting solution was saved for further modeling. In a later sensitivity analysis, the applied water was doubled to 20,000 gallons per week and there was virtually no change in the final model results (described below).

It was assumed that this soil moisture content will be 6% by weight during the operations period (DOE-ID 2000). Further, assuming 1 kg of applied water corresponds to 1 liter, each liter of leachate would be exposed to 16.7 kg of landfill soil. In the geochemical model, 1 liter of the water mixture described above was equilibrated with specified molar quantities of minerals present in 16.7 kg of soil.

The second step of the geochemical modeling was to assign mineral phases to site soil and/or controls on constituent solubility. Mineralogy (with average percent abundance) reported in soils on the

a. Provided by Marty Doornbos in a personal communication to CH2M HILL, 2001.

Chemical Processing Plant consisted of quartz, plagioclase feldspar, potassium feldspar, calcite, pyroxene, and detrital mica (USGS 1989). Simplifying assumptions were made to assign specific minerals to plagioclase (albite), potassium feldspar (orthoclase), pyroxene (enstatite), and mica (illite). The average percent abundance of each mineral was converted to g/kg with the assumption that the minerals have approximately equal density. The g/kg concentrations were converted to total grams by multiplying by 16.7, the total kg exposed to each liter of leachate (see above). Finally, the grams of each mineral were converted to moles by dividing by the molecular weight of each mineral. The calculations are summarized in Table 2-1.

Table 2-1. Calculation of mineral abundance in site soils.

	Quartz	Albite (plagioclase feldspar)	Orthoclase (potassium feldspar)	Calcite	Enstatite (pyroxene)	Illite (mica)
Average abundance (%) ^a	38.3	22.7	13	3.7	13	9.3
g/kg soil	383	227	130	37	130	93
mineral molar mass (g/mol)	60	262	278	100	100	383.5
mol/kg soil	6.39	0.87	0.47	0.37	1.30	0.24
mol exposed to 1 L leachate ^b	39.5	5.3	2.9	2.3	8.0	1.5

a. Average of BLRB-7, BLRB-8, and BLRB-9 (USGS 1989).

b. Calculated by multiplying mol/kg by 6.18 kg soil per L void space (see text).

Some of the soil minerals listed above are typically not in direct equilibrium with pore water in natural environments. Feldspars will have a microscopic layer of clay mineral on the weathering surface. Though minute in overall mass concentration, this clay mineral (kaolinite was assigned for modeling purposes) controls the aqueous concentrations of aluminum and silicon. As magnesium-rich minerals such as enstatite dissolve, the aqueous concentration of magnesium is typically controlled by dolomite in this environment. Kaolinite and dolomite were input to PHREEQC only as solubility controls, not as quantified masses.

Inventory elements not accounted for by the calculations in Table 2-1 were assigned to realistic solid phases based on the geochemical environment (i.e., oxidizing, neutral to slightly alkaline conditions). Metal cations were commonly assigned oxides, hydroxides, or carbonates that form in near-surface regimes. Although not expected in oxidizing environments, significant sulfide was reported in the inventory. To account for this mass, the common sulfide minerals pyrite (FeS₂) and sphalerite (ZnS) were included. In a soil environment open to the atmosphere such as this one, equilibrium calculations predict that all sulfides will be oxidized to sulfate and dissolve. Zincite (ZnCO₃) was used as a control on zinc solubility, and ferric hydroxide (Fe(OH)₃) was used both as a source of iron and a control on its solubility. A list of the screened elements and their mineral source(s) and control(s) is provided in Appendix A as Table A-5. Some design inventory contaminants will likely exist in soluble solid forms such as sodium salts. During water infiltration they would dissolve and reprecipitate as the modeled phases described above. To eliminate guessing the solid forms in the waste stream, the modeling was accomplished by assigning the stable solid phases and calculating the concentration of the solution in equilibrium with these phases.

Two very soluble anions, cyanide (CN⁻) and iodide (I⁻), were not represented by realistic minerals in the LLNL database. To account for these constituents, they were added as sodium salts under the reasonable assumption of complete dissolution.

One liter of the infiltrating water mixture was equilibrated with the molar quantities of the minerals listed in Table A-5. Because the system is open to the atmosphere during the operating period, the system was also equilibrated with atmospheric oxygen (P_{O2} = 0.2 atm) and carbon dioxide (P_{CO2} = 10^{-3.5} atm). Redox potential was calculated on the basis of oxygen fugacity and pH was calculated as part of the equilibration process.

2.4 Results of Geochemical Modeling

The modeled concentrations of the screened elements are reported in Table 2-2. The complete PHREEQC input and output files are provided in Appendix B. The modeled leachate is a brackish water (total dissolved solids around 46,000 mg/L) dominated by sodium and sulfate with a pH of 8.0. The water chemistry is most influenced by the oxidation of sulfide minerals, equilibration of carbonates, and dissolution of the more plentiful of the soluble components of the design inventory (such as boron, phosphorus, terbium, vanadium, and ytterbium, along with the major elements).

Elements that were only slightly soluble included barium, zinc, plutonium, and uranium. Salts of most anionic constituents were completely dissolved before equilibration could be reached. These constituents included chloride, iodide, technetium, selenium, and arsenic.

These results represent an approximation of chemical conditions. The mineral phases were chosen on the basis of the best available data and what were considered reasonable assumptions regarding the geochemical environment. As discussed above, the model predicted complete oxidation of sulfide due to the equilibration condition with atmospheric oxygen. This process may be limited during the operation period by chemical kinetics, but insufficient data were available for quantification.

Partition coefficients (K_d values) were not applied during the geochemical modeling stage. The leachate generation calculations described in Section 3 involved application of K_d values and radioactive decay.

Table 2-2. Results of PHREEQC simulation: calculated constituent concentrations in leachate (no partitioning applied).

	Constituent	mol/kg H ₂ O ^a	mol/L	Molar Mass	mg/L
Aluminum	Al	5.29E - 08	4.97E - 08	26.98	1.3E - 03
Arsenic	As	1.28E - 03	1.20E - 03	74.9	9.0E + 01
Boron	B	2.46E - 01	2.31E - 01	10.8	2.5E + 03
Barium	Ba	2.05E - 08	1.92E - 08	137	2.6E - 03
Carbon (rad) ^b	C		not calculated	14	6.4E - 11
Carbon (non-rad)	C	6.69E - 02	6.28E - 02	12	7.5E + 02
Calcium	Ca	1.09E - 02	1.03E - 02	40	4.1E + 02
Chlorine	Cl	1.14E - 03	1.07E - 03	35.5	3.8E + 01
Fluoride	F	1.28E - 03	1.20E - 03	19	2.3E + 01
Iron	Fe	4.66E - 07	4.38E - 07	55.847	2.4E - 02
Iodine (rad)	I	1.01E - 06	9.49E - 07	129	1.2E - 01

Table 2-2. (continued).

	Constituent	mol/kg H ₂ O ^a	mol/L	Molar Mass	mg/L
Potassium	K	3.56E - 04	3.35E - 04	39.1	1.3E + 01
Magnesium	Mg	9.26E - 04	8.70E - 04	24.3	2.1E + 01
Manganese	Mn	6.06E - 13	5.70E - 13	54.9	3.1E - 08
Sodium	Na	3.63E - 01	3.41E - 01	23	7.8E + 03
Nitrate	NO ₃	1.29E - 03	1.22E - 03	62	7.5E + 01
Phosphorus	P	3.83E - 03	3.60E - 03	31	1.1E + 02
Plutonium (rad)	Pu	3.09E - 13	2.90E - 13	244	7.1E - 08
Selenium	Se	1.92E - 04	1.80E - 04	79	1.4E + 01
Sulfate	SO ₄	2.24E - 01	2.10E - 01	96	2.0E + 04
Tellurium (rad) ^b	Te		not calculated	128	1.5E - 10
Silicon	Si	1.07E - 04	1.00E - 04	28	2.8E + 00
Terbium	Tb	6.39E - 02	6.00E - 02	158.9	9.5E + 03
Technitium (rad)	Tc	6.09E - 08	5.72E - 08	98.9	5.7E - 03
Uranium (rad)	U	3.63E - 06	3.41E - 06	238	8.1E - 01
Vanadium	V	7.45E - 03	7.00E - 03	50.9	3.6E + 02
Ytterbium	Yb	2.00E - 02	1.88E - 02	173	3.3E + 03
Zinc	Zn	1.29E - 04	1.21E - 04	65.4	7.9E + 00

a. Due to dissolution of significant quantities of mineral phases, the density of leachate is calculated to be 1.064 kg/L

b. These constituents were not modeled in PHREEQC; concentration represents complete dissolution.

3. LEACHATE GENERATION RATE AND CONTAMINANT REDUCTION OVER TIME

Application of partitioning coefficients (K_d values) to the design inventory mass estimates was used to evaluate the contaminant mass adsorbed to the soil and the mass contained in the aqueous phase. The resulting concentrations were then determined on the basis of the total mass of soil estimated to be disposed in the landfill, and the design moisture content, respectively. Annual leachate losses, combined with radioactive and environmental decay, were used to calculate changes in leachate and landfill composition over the operating period. The methodology and results for each group are presented below.

3.1 Leachate Generation

3.1.1 Introduction

An analytical solution was applied to estimate the loss of the design inventory contaminants from the emplaced waste in the ICDF during the period of time that the landfill is in operation and prior to placement of the final cover. This model is intended to support decisions regarding waste placement and to facilitate understanding of the mobility of contaminants within the facility. The approach and methodology used in this evaluation are described in the following sections.

3.1.2 Approach

An analytical model utilizing Microsoft Excel™ spreadsheet tools was prepared. The spreadsheet format allows rapid development of the model and ease of modification of specific input parameters to support sensitivity analyses. Input to the model includes the ICDF design inventory for contaminants, estimated waste mass and volume, and project-specific distribution/partition coefficients (K_d) for site contaminants. The model utilizes simplified assumptions regarding moisture content of the waste soil within the landfill and water recharge through the emplaced waste. The details of the model methodology are described in Section 3.1.3.

3.1.3 Methodology

The inventory and release model estimated the concentration of each contaminant in the leachate exiting the ICDF yearly, and the amount of contaminant mass remaining within the ICDF. These parameters were modeled over a 15-year period during which the landfill is assumed to be filled to capacity and before placement of the cover. The model assumptions and computational details are described in the following subsections.

3.1.3.1 Assumptions. The following assumptions were applied to support development of the analytical model:

- The landfill was assumed to be filled to capacity at the start of the computations (i.e., the design volume of waste soil is in place at time zero [T_0], or the start of the simulation).
- The uniform waste soil moisture is assumed to be 6% by weight (DOE-ID 2000) at the beginning of the simulation, and remain unchanged during the 15-year period.
- The initial leachate concentration was assumed to be the contaminant mass present in the design inventory, distributed between the solid and solution phases according to the site-specific distribution coefficients (K_d).

- All contaminants of concern were included in the simulation.
- Contaminant mass leaves the landfill only by leachate transport and/or by radioactive or environmental decay, as applicable.

3.1.3.2 Computations. Contaminant mass exited the ICDF only by means of leachate transport and/or radioactive or environmental decay. The model essentially consisted of determining the equilibrium concentration of each contaminant in solution and on solids contained within the ICDF, and then calculating the amount of leachate exiting the ICDF. Thus, the amount of contaminant remaining in the ICDF equaled the initial mass minus the mass transported by the leachate and the mass lost to radioactive decay.

Beginning with the initial inventory for each contaminant, the total mass (m_T) equaled the mass of contaminant on the solids (m_s) and the mass of contaminant in solution (m_{aq}):

$$m_T = m_s + m_{aq} \quad \text{or} \quad m_T = c_s M + c_{aq} V \quad (1)$$

Where

The contaminant concentration on the solids (c_s) equals the mass of the contaminant on the solids divided by the total mass content of the ICDF (M), and the contaminant concentration in solution (c_{aq}) equals the mass of contaminant in solution divided by the total water content of the ICDF (V). The ICDF moisture content of 6% by weight was assumed at the start of the simulation time with no change occurring in the water content. At equilibrium, the distribution coefficient (k_d) equals the ratio the contaminant concentration on the solids to the contaminant concentration in solution:

$$k_d = \frac{c_s}{c_{aq}} \quad (2)$$

Combining the two equations results in the following relationships:

$$c_{aq} = \frac{m_T}{(k_d M + V)} \quad \text{and} \quad c_s = k_d c_{aq} \quad (3)$$

The mass of contaminant exiting the ICDF each year equals the leachate concentration multiplied by the leachate volume (v_i), and the mass remaining (m_{Ti+1}) is the initial mass minus the leachate mass, less the mass lost to radioactive or environmental decay:

$$m_{Ti+1} = m_{Ti} * e^{-\ln(2)/T_{1/2}} - c_{aq} v_i \quad (4)$$

Where

$T_{1/2}$ is the half-life of the radioactive isotope or organic compound. For non-decaying contaminants ($T_{1/2} = 0$), the exponential term equals 1. The contaminant concentrations for the following year are then calculated using the remaining total mass, and the preceding contaminant concentration equations.

3.1.3.3 Model Input Parameters. The naturally occurring background recharge for the INEEL site is estimated to be 1.0 centimeters (cm) per year. Because of the trapezoidal shape of the landfill,

estimated water recharge through the landfill waste mass was increased according to the ratio of the top of the landfill to the bottom of the landfill (1.74:1, see Section 4.1.3 for a complete explanation). Thus the simulation was performed using a recharge rate of 1.74 cm per year or 0.0174 m/yr.

The initial mass of moisture in the landfill equals the moisture content (by weight) multiplied by the mass of soil in the landfill. The design inventory is $5.85\text{E} + 08$ kg of waste, so the initial mass of water is $3.51\text{E} + 07$ kg of water. At an assumed water density of 1.0 kg/L, the initial volume of water equals $3.51\text{E} + 07$ L. The volume of water exiting the landfill each year equals the ratioed recharge rate multiplied by the area of the bottom of the landfill ($0.0174 \text{ m/yr} * 160 \text{ m} * 194 \text{ m}$): $5.40\text{E} + 02 \text{ m}^3/\text{yr}$ or $5.40\text{E} + 05 \text{ L/yr}$.

3.1.4 Simulation Output and Discussion

Concentrations of all constituents from Table A-1 were calculated for each year of the operation period, and the results are presented in Appendix C of this report. The leachate reduction simulation indicates that contaminant mass reduction due to leaching of selected highly mobile contaminants (i.e., iodine-129 and tritium, technetium-99, and neptunium-237) is typically around 20% of the design inventory mass over the 15-year simulation period at the background recharge rate. Iodine-129 was assigned a K_d of zero, and therefore represents the most conservative conditions. Technetium-99 has a K_d value of 0.2 ml/g and experienced a contaminant reduction of approximately 5%. The uranium isotopes and neptunium-237 have K_d values of 6.0 and 8.0 ml/g, respectively, and experienced contaminant reductions of less than 1%. The leachate concentration and residual contaminant mass for the selected iodine, technetium, and neptunium isotopes for the 15-year simulation period at the 1.0 cm/yr recharge rate are shown in Figure 3-1.

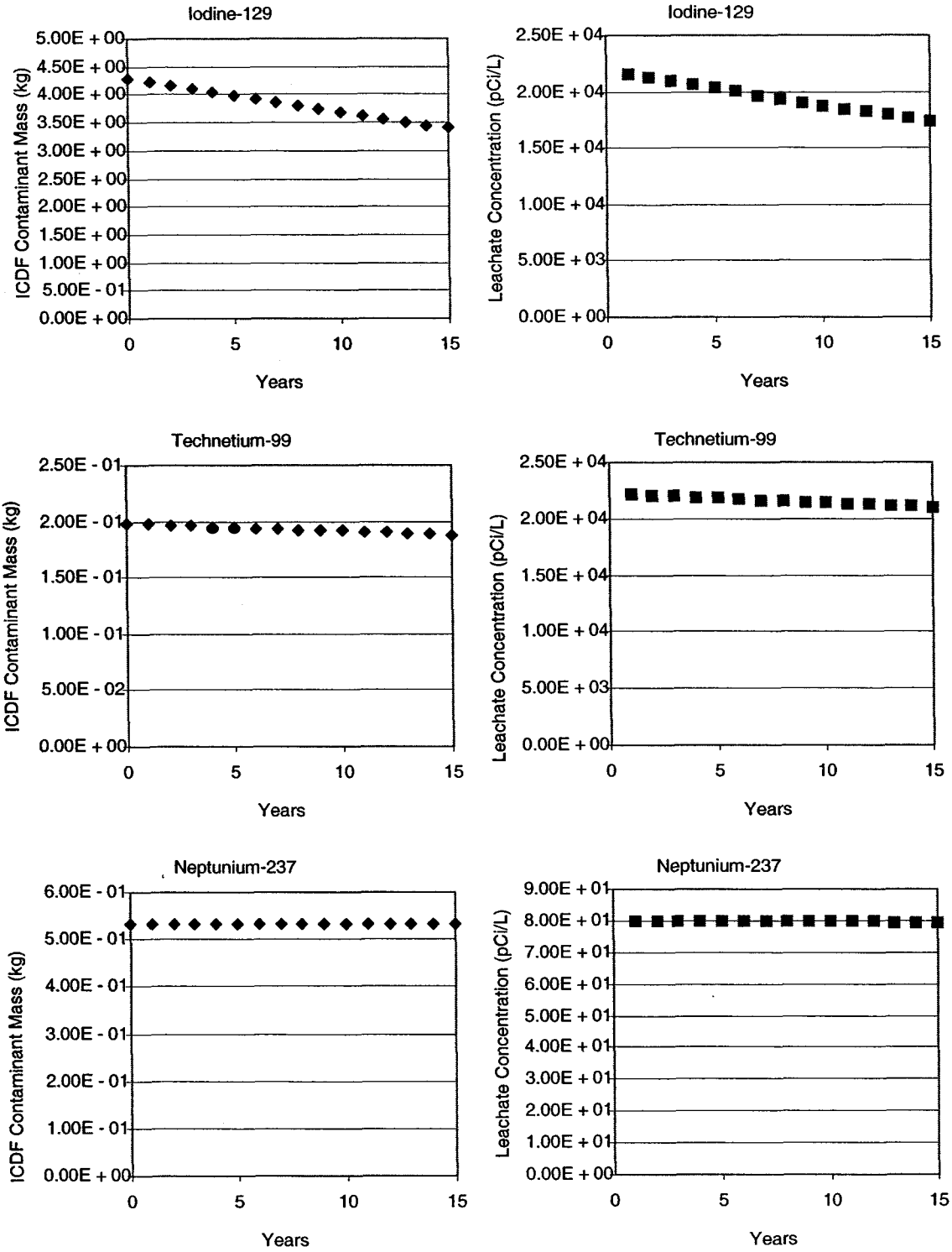


Figure 3-1. Evaluation of leachate concentration and residual mass in the ICDF at background recharge ratioed to 1.74 cm/yr recharge.

4. LEACHATE GENERATION AND CONTAMINANT REDUCTION DURING POST-CLOSURE PERIOD

An estimate of leachate generation and landfill contaminant migration in leachate during the 30-year post-closure period was performed using the same two-dimensional numerical code used to perform the landfill fate and transport modeling (i.e., STOMP). The simulation provides dilution/attenuation factors (DAF) for leachate that can be applied to design inventory constituents to determine estimated leachate concentration based on given landfill source concentrations. The simulation input parameters and overall physical conceptual model are described in detail in "Fate and Transport Modeling Results" (EDF-ER-275). To modify the model for assessment of the leachate generation, the top of the clay layer of the landfill liner was assumed to be a no-flow boundary to simulate the presence of the synthetic liner component. In addition, the sides of the operations layer immediately overlying the synthetic liner was assumed to be a seepage face, allowing leachate to exit the system when local hydraulic head exceeded atmospheric pressure.

A group of surrogates was selected to represent the entire list of contaminants of concern. Contaminants were assigned a surrogate only on the basis of relative mobility based on their distribution coefficients (K_d). For radioactive or environmentally decaying contaminants, the breakthrough curves of the appropriate surrogates were decayed individually. The methodology and results for the evaluation of leachate generation and constituent migration are presented below.

4.1 Leachate Generation Simulation

4.1.1 Introduction

The STOMP code was used to simulate leachate generation curves for the landfill. This model is intended to support decisions regarding leachate management and evaporation pond management during the post-closure period and to facilitate understanding of the mobility of contaminants within the facility. The approach and methodology used in this evaluation are described in the following sections.

4.1.2 Approach

This section describes the methods used to simulate the volume and contaminant concentrations of leachate collected during the 30-year post-closure period of the ICDF. During the post-closure period, the cap and the liner are assumed to remain intact and function as designed. The 60% design two-dimensional (vertical and horizontal parallel to groundwater flow) numerical model used to simulate the contaminant transport from the ICDF was amended to conduct the simulations. Hydraulic properties and ICDF construction parameters remained the same, with the exception that the top of the clay layer changed to a no-flow boundary to simulate the functioning synthetic liner. The side boundaries of the model remained no-flow, except immediately above the clay, where the boundary allowed flow and contaminants to exit the model domain when the local hydraulic pressure exceeded atmospheric pressure (seepage boundary). The flow exiting the model through these boundaries represented the leachate collected during the post-closure period.

4.1.3 Methodology

The modeling effort used the STOMP version 2.0 finite difference code developed by Pacific Northwest National Laboratory (PNNL) to conduct the simulations. A description of the STOMP code is found in the Theory Guide (PNNL-11217 1996) and the User's Guide (PNNL-12034 2000). Quantitative predictions of hydrogeologic flow and contaminant transport are generated from the numerical solution of

non-linear partial differential equations that describe subsurface environment flow and transport phenomena. STOMP capabilities include, among others, the simulation of saturated and unsaturated flow regimes, transport of radioactive elements and non-decaying contaminants, and transport of aqueous phase and non-aqueous phase organic compounds. A complete description of STOMP capabilities, the actual equations, and the partial differential approximations are contained within the Theory Guide and User's Guide and are not repeated here, except where necessary to describe input parameters.

The length dimension of the ICDF facility in the numerical model was determined from preliminary construction drawings (DOE-ID 2002) to be about 160 m. The side slope of the facility is ~3:1, so for the estimated waste volume (510,000 yd³ or 389,923 m³), the slope of the sides increases the area at the top of the waste by a factor of ~1.74:1. Therefore, the simulation of leachate accumulation increased by the specified design recharge rate (0.0001 m/yr) by a factor of 1.74. To account for the width of the facility, the leachate volume calculated to exit the model boundaries was multiplied by 194, which represented the width dimension determined from preliminary construction drawings (DOE-ID 2002). The concentration of the contaminants was assumed to remain uniform across the width of the facility.

4.1.3.1 Assumptions. The following assumptions were applied to support development of the leachate generation model:

1. The landfill was assumed to be filled to capacity at the start of the simulation (i.e., the design volume of waste soil is in place at time zero [T_0], or the start of the simulation).
2. The initial waste soil moisture content is assumed to be at equilibrium with a steady state background recharge of 0.01 m/yr. It should be noted that while heavier precipitation events would be anticipated to produce larger quantities of leachate, precipitation pulses would tend to be attenuated or buffered to some degree by waste in the landfill.
3. The final landfill cover is assumed to be in place for the duration of the entire simulation, with net recharge to the landfill at the selected maximum design recharge rate of 0.0001 m/yr.
4. Contaminant mass leaves the landfill only by leachate transport and/or by decay (i.e., radioactive decay or environmental degradation), as applicable.
5. The synthetic high-density polyethylene (HDPE) liner component is assumed to be in place and to provide an impermeable layer at the top of the clay liner component for the duration of the simulation.
6. The lateral sides of the landfill model domain are assumed to be seepage boundaries that permit flow of leachate when local hydraulic pressure exceeds one atmosphere.
7. The simulation period is assumed to be limited to the 30-year post-closure period.
8. There are assumed to be no limits to solubility of the waste constituents simulated.

4.1.3.2 Computations. Simulating water and contaminant transport through the vadose zone requires the solution of the non-linear partial differential equations used to describe flow through unsaturated porous media. Solution of the equations requires moisture retention (aqueous phase pressure and moisture content) and fluid transport (hydraulic conductivity and moisture content or aqueous phase pressure) characteristic data for the porous media contained within the model domain. The model uses functional relationships (referred to as characteristic curves) to describe the characteristic data. The

equation used in the model was developed by van Genuchten to describe the moisture retention characteristic of the porous media:

$$S_w = \left\{ 1 + \left(\alpha \left[\frac{P_g - P_w}{\rho_w g} \right]^n \right)^{-m} \right\} \quad \text{for } P_g - P_w > 0$$

$$S_w = 1 \quad \text{for } P_g - P_w \leq 0$$
(5)

Where

S_w = degree of water saturation of the porous media (dimensionless)

P_g = absolute pressure of the gas phase present (Pa, atmospheric pressure for these simulations)

P_w = absolute pressure of the water phase present (Pa)

ρ_w = density of water (kg/m^3)

g = acceleration of gravity (m/s^2)

α ($1/\text{m}$), n , and m are curve fit parameters, and $m = 1 - 1/n$ except for basalt.

The Mualem equation was used to describe hydraulic conductivity as a function of moisture content:

$$k_{rw} = (S_w)^{1/2} \{ 1 - (1 - [S_w]^{1/m})^m \}^2 \quad \text{and}$$

$$K = k_{rw} * K_{sat}$$
(6)

Where

K_{sat} = permeability (cm^2) or hydraulic conductivity (cm/s)

k_{rw} = relative permeability or hydraulic conductivity

K_{sat} = saturated permeability (cm^2) or saturated hydraulic conductivity (cm/s)

S_w and m are defined as before.

Table 4-1 presents the characteristic curve parameters of the different layers used in the leachate simulation, and Table 4-2 presents the hydraulic properties for the different layers. The saturated moisture content of each model layer type was assumed to equal the porosity. The surrogate distribution coefficients for the surrogates in the waste and operations layers are shown in Table 4-3.

Table 4-1. Summary of soil properties and moisture content-aqueous pressure relationship curve fit parameters.

Model Layer Type	Saturated Moisture Content	Residual Moisture Content	Curve Fit Parameter α (1/m)	Curve Fit Parameter n	Curve Fit Parameter m
Clay	Top of Clay is No-Flow Boundary				
Operations Layer	0.275	0.083	1.066	1.523	0.343
Waste	0.266	0.072	1.066	1.523	0.343

Table 4-2. Summary of soil hydraulic and contaminant transport properties.

Model Layer Type	Bulk Density (kg/m ³)	Saturated Hydraulic Conductivity (cm/s)	Longitudinal Dispersivity (m)	Transverse Dispersivity (m)
Clay	Top of Clay is No-Flow Boundary			
Operations Layer	1922	1E - 04	5	0
Waste	1946	1E - 03	5	0

Table 4-3. Contaminant distribution coefficients and weighted averages for the different surrogates and model layer types.

Model Layer Type	Distribution Coefficient (K_d) (cm ³ /g)							
	Surrogate 1	Surrogate 2	Surrogate 3	Surrogate 4	Surrogate 5	Surrogate 6	Surrogate 7	Surrogate 8
Operations Layer	0	0	0.2	6	8	24	16	340
Waste	0	0	0.2	6	8	12	16	340

4.1.4 Simulation Output and Discussion

The results of the model indicate that no leachate accumulates after the cover is placed until the fourth year of the post-closure period.^b The coincident arrival of the contaminants results from the fact that the transport tends to be dominated by drainage of initial moisture and diffusion at the design recharge rate. Also, the water must accumulate in the seepage boundary cells until the hydraulic pressure exceeds atmospheric pressure and the capillary pressure of the operations layer. The maximum simulated leachate generation rate is approximately $2.14\text{E} + 04$ L/yr, and cumulative leachate volume for the simulation period is estimated at $4.23\text{E} + 05$ liters (Figure 4-1). The more mobile contaminants may have arrived at the boundary cells sooner than the much less mobile contaminants, but transport across the seepage boundary did not occur until all the contaminants were present in the leachate. As indicated in Table 4-4, the leachate concentration of any contaminant less mobile than uranium is a small fraction of the waste soil concentration, and no significant percentage of any contaminant is collected in the leachate, even though the concentrations may be greatly elevated.

b. Note that the actual leachate flow is expected to transition from the operational period through the post-closure period.

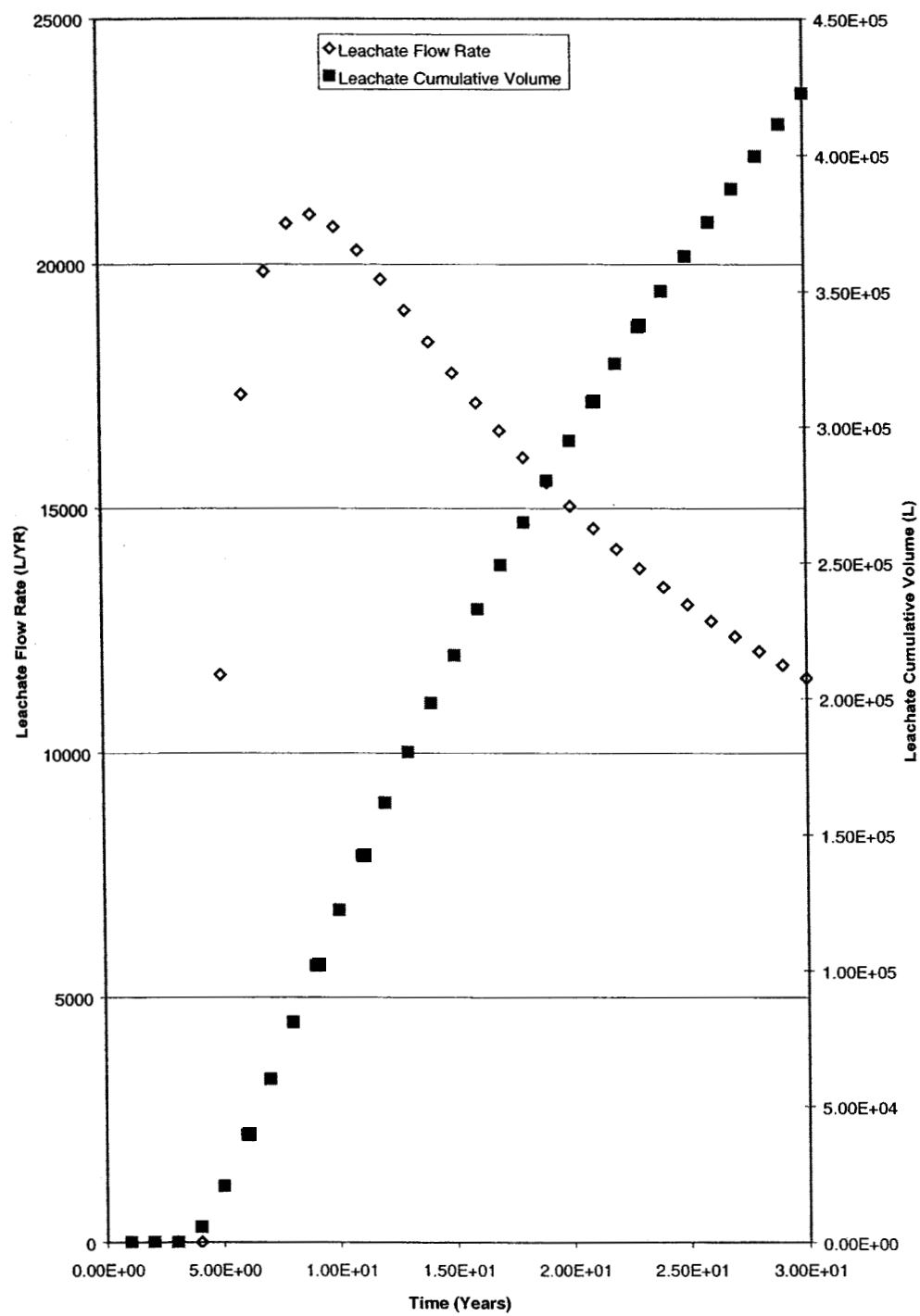


Figure 4-1. Leachate generation rate and cumulative leachate volume for the 30-year post-closure simulation period.

Table 4-4. Summary of Post-Closure Leachate Modeling Results at 0.0001 m/yr Recharge Rate.

	Half-Life (yr)	Design Inventory Concentration (mg/kg or pCi/kg)	Model Surrogate	Maximum Concentration (mg/L or pCi/L)	Average Concentration (mg/L or pCi/L)	Percentage of Inventory in Leachate
Radionuclides						
H-3	1.24E + 01	4.96E + 04	Surrogate 1	1.10E + 05	8.39E + 04	0.12%
I-129	1.57E + 07	1.30E + 03	Surrogate 2	7.36E + 03	5.80E + 03	0.32%
Tc-99	2.13E + 05	5.76E + 03	Surrogate 3	8.05E + 03	5.29E + 03	0.07%
U-234	2.45E + 05	6.03E + 03	Surrogate 4	4.22E + 00	1.57E + 00	0.00%
U-235	7.04E + 08	1.10E + 02	Surrogate 4	7.72E - 02	2.88E - 02	0.00%
U-236	2.34E + 07	2.02E + 02	Surrogate 4	1.42E - 01	5.28E - 02	0.00%
U-238	4.47E + 09	1.95E + 03	Surrogate 4	1.37E + 00	5.10E - 01	0.00%
Np-237	2.14E + 06	6.43E + 02	Surrogate 5	1.64E - 01	5.99E - 02	0.00%
Co-60	5.27E + 00	1.93E + 05	Surrogate 5	1.53E - 00	1.10E + 00	0.00%
Sr-90	2.91E + 01	2.29E + 07	Surrogate 6	6.52E + 02	2.74E + 02	0.00%
Pu-239	2.41E + 04	6.66E + 03	Surrogate 7	1.32E - 01	4.68E - 02	0.00%
Pu-240	6.54E + 03	1.50E + 03	Surrogate 7	2.97E - 02	1.05E - 02	0.00%
Cs-137	3.00E + 01	2.44E + 07	Surrogate 8	1.48E - 03	5.92E - 04	0.00%
Eu-155	4.96E + 00	1.76E + 05	Surrogate 8	5.09E - 07	3.65E - 07	0.00%
Organic						
Tributylphosphate	1.16E + 00	3.64E - 01	Surrogate 1	4.43E - 02	5.37E - 03	0.00%
2-Nitroaniline	NA	2.72E - 02	Surrogate 2	1.54E - 01	1.22E - 01	0.32%
Benzene	1.00E + 00	6.03E - 01	Surrogate 2	-5.01E - 02	-5.19E - 03	0.00%
Toluene	4.79E - 02	9.82E - 01	Surrogate 3	-7.97E - 27	-2.94E - 28	0.00%
Xylene (total)	5.12E - 01	3.45E + 00	Surrogate 3	-1.62E - 03	-1.02E - 04	0.00%
Dibenzofuran	5.94E - 02	3.24E - 01	Surrogate 7	-8.90E - 29	-3.29E - 30	0.00%
Aroclor-1260	3.88E - 02	7.21E - 01	Surrogate 6	-1.69E - 44	-6.24E - 46	0.00%
Chrysene	3.76E + 00	2.65E - 01	Surrogate 8	3.73E - 13	2.46E - 13	0.00%
Inorganic						
Sulfate	NA	2.05E + 01	Surrogate 1	1.16E + 02	9.18E + 01	0.32%
Sulfide	NA	7.59E + 02	Surrogate 1	4.30E + 03	3.39E + 03	0.32%
Cyanide	NA	3.37E - 01	Surrogate 2	1.91E + 00	1.51E + 00	0.32%
Arsenic	NA	5.65E + 00	Surrogate 7	1.12E - 04	3.97E - 05	0.00%
Boron	NA	1.85E + 02	Surrogate 3	2.58E + 02	1.70E + 02	0.07%
Molybdenum	NA	1.02E + 01	Surrogate 5	2.59E - 03	9.48E - 04	0.00%
Cadmium	NA	3.59E + 00	Surrogate 4	-2.51E - 03	-9.37E - 04	0.00%
Cobalt	NA	6.04E + 00	Surrogate 5	-1.54E - 03	-5.62E - 04	0.00%

Table 4-4. (continued).

	Half-Life (yr)	Design Inventory Concentration (mg/kg or pCi/kg)	Model Surrogate	Maximum Concentration (mg/L or pCi/L)	Average Concentration (mg/L or pCi/L)	Percentage of Inventory in Leachate
Aluminum	NA	7.08E + 03	Surrogate 7	1.40E - 01	4.97E - 02	0.00%
Lead	NA	5.76E + 01	Surrogate 7	1.14E - 03	4.05E - 04	0.00%
Zirconium	NA	6.91E + 01	Surrogate 8	8.39E - 09	2.88E - 09	0.00%

The leachate generation simulation can be extrapolated to all the constituents in the landfill design inventory by correlating the K_d s of the constituents in the design inventory to the K_d s of the simulated surrogates. As shown in the simulation results (Table 4-4), no significant quantity of the inventory of any constituents similar to, or less mobile than, surrogate 4 are removed from the system in the post-closure period. Appendix D presents the simulated peak aqueous concentration for leachate during the post-closure period using a beginning inventory based on the facility design inventory.

5. CONCLUSIONS

Concentrations of design inventory constituents in ICDF landfill leachate were simulated over the 15-year operations period and an assumed 30-year post-closure period. The purpose of the study was to examine the change in landfill contaminant mass and leachate concentration over time. As long as the landfill is generating leachate, it will be managed in a manner that is protective of human health and the environment, and in accordance with all ARARS.

The conclusions of each evaluation include the following:

- **Geochemical Modeling**
 - Detailed discussion of results are found in Section 2.3 with output provided in Appendix B.
 - Leachate is a brackish water (total dissolved solids around 46,000 mg/L) dominated by sodium and sulfate with a pH of 8.0.
 - The water chemistry is most influenced by the oxidation of sulfide minerals, equilibration of carbonates, and dissolution of the more plentiful of the soluble components of the design inventory.
 - Elements that were only slightly soluble include barium, zinc, plutonium, and uranium.
 - Salts of most anionic constituents were completely dissolved before equilibration could be reached.
- **Leachate Generation During Operations**
 - Detailed discussion of results are found in Section 3.1.4 with output provided in Appendix C.
 - Contaminant mass reduction due to leaching of selected highly mobile contaminants is typically around 20% of the design inventory mass over the 15-year simulation period.
 - Technitium-99 has a K_d value of 0.2 ml/g and experienced a contaminant reduction of approximately 5%.
 - Uranium isotopes and neptunium-237 have K_d values of 6.0 and 8.0 ml/g, respectively, and experienced a contaminant reduction of less than 1%.
- **Leachate Generation During Post-Closure**
 - Detailed discussion of results are found in Section 4.1.4 with output provided in Appendix D.
 - Less than 1% of the inventory masses of the most mobile constituents may be removed in leachate during that time period.
 - The decrease in contaminant mass leached is primarily due to the expected substantial reduction in leachate generation provided by the effective function of the final landfill cover system.

6. REFERENCES

- Brownlow, A.H., 1996, *Geochemistry*, 2nd edition, Prentice-Hall: Upper Saddle River, New Jersey, 580 p.
- DOE-ID, 2002, *INEEL CERCLA Disposal Facility Remedial Design/Construction Work Plan*, DOE/ID-10848, Rev. 1, Appendix Z, "INEEL CERCLA Disposal Facility - Drawings," U.S. Department of Energy Idaho Operations Office, Idaho Falls, Idaho, May 2002.
- DOE-ID, 2000, *Geotechnical Report for the Conceptual Design of the INEEL CERCLA Disposal Facility at Waste Area Group 3, Operable Unit 3-13*, DOE/ID-10812, Rev. 0, Department of Energy Idaho Office Operations, Idaho Falls, Idaho.
- EDF-ER-264, 2001, "INEEL CERCLA Disposal Facility Design Inventory," Rev. A, Environmental Restoration Program, Idaho National Engineering and Environmental Laboratory, March 2001.
- EDF-ER-269, 2002, "Leachate Generation Study," Rev. 1, Environmental Restoration Program, Idaho National Engineering and Environmental Laboratory, May 2002.
- EDF-ER-275, 2002, "Fate and Transport Modeling Results," Rev. 2, Environmental Restoration Program, Idaho National Engineering and Environmental Laboratory, May 2002.
- NOAA, 1989, *Climatology of the Idaho National Engineering Laboratory*, 2nd edition, National Oceanic and Atmospheric Administration.
- Parkhurst, D. L. and C. A. J. Appelo, 1999, "User's Guide to PHREEQC (Version 2): A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations," *U.S. Geological Survey Water-Resources Investigations Report 99-4259*, 312 p. Compiled program (Version 2.3) available at <http://water.usgs.gov/software/phreeqc.html>.
- USGS, 1989, *Minerology and Grain Size of Surficial Sediment from the Big Lost River Drainage and Vicinity, with Chemical and Physical Characteristics of Geologic Materials from Selected Sites at the Idaho National Engineering Laboratory, Idaho*, U.S. Geological Survey Open-File Report 89-384, United States Geological Survey.